Appendix C
Rotor Modeling Data Requirements
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The following text was supplied by Marshall Buhl in the spring of 1995 and covers his many experiences building rotor models with ADAMS. It is reproduced in its entirety because it contains many excellent modeling hints and again emphasizes the need for good descriptive data for any new turbine model. Thanks, Marshall.

MODELING WIND TURBINES WITH *ADAMS*®

INTRODUCTION

What follows are guidelines for the kind of information that you will need to model a "complete" wind turbine with *ADAMS*. The information here is not at all exhaustive. It does, however, represent the collective knowledge of two years of experience gained by National Renewable Energy Laboratory (NREL) engineers while using *ADAMS* to model wind turbines. If you save the following information as you design a new turbine, you will have an excellent start on an *ADAMS* model. Please remember that the more accurate your input data, the better your results will be. You will have to make the tradeoff between the required effort to improve your input data and the benefits of a more accurate simulation.

We break the turbine into each of its major subsystems and describe them in detail below. We attach a table of parameters to the end of the document to make it easier for you to keep track of your data requirements.

TOWER:

You can model your tower as a rigid structure that has no effect on the system dynamics or as a collection of lumped masses separated by flexible, force-at-a-distance "beams" or "fields."

For the first method, you model the tower as part of the ground; the geometry of the tower is the only information needed. We often do this to simplify the model for special cases, or to check other subsystems.

NREL engineers usually use the second method to model towers. The difference between beams and fields is that beams assume uniform properties between the two lumped masses. Most towers have only a slight taper (if any), so we believe that beams are sufficiently accurate and that fields do not merit the additional modeling efforts they require. If your tower is highly tapered, you should consider using fields.

Whether you use beams or fields to model your tower, break the tower into five to ten lumped masses, depending upon stiffness (you will not need as many for stiffer towers). For each mass, you need the location of the centers of mass, masses, and mass moments of inertia about all three axes.

For beams, *ADAMS* requires the cross sectional areas, the area moments of inertia about each axis, Young's modulus, and the shear modulus for each beam. *ADAMS* uses these values to compute a stiffness matrix.

When using fields, you must specify a stiffness matrix instead of the inertias, areas, and moduli— though you will probably need them to create your own stiffness matrix.

For both beams and fields, you need to supply beam lengths and a damping "ratio." *ADAMS* multiplies each element of the stiffness matrix by the damping ratio to generate a damping matrix. You can supply your own damping matrix if you desire.

If you have a guyed tower, you will need to know the geometry, spring constant, damping constant, and the pretension in the guys to model the guys as massless springs. If the inertia of the guys is large enough to affect overall system dynamics, you may want to model them as a flexible subsystem. If so, follow the lumped-mass approach outlined above, but use spring/dampers between the masses instead of beams or fields.

Even though it has no impact upon dynamics, you will probably want to generate a graphic that approximates the shape of the tower for animation purposes. For this, you will need the tower geometry. The current version of *ADAMS* can draw lines, spheres, cylinders, frustums, boxes, and other simple graphics objects.

NACELLE:

We have modeled nacelles as rigid bodies. We do not include in the nacelle the parts of the drive train we wish to model separately. You will need to know the mass, center of mass, mass moments of inertia, and geometry of the nacelle. Even if you lock or drive the machine yaw, this information will affect tower modes. You will also need an accurate measurement of the location of the yaw bearing and the low speed shaft (LSS).

You can obtain the mass and mass moments of inertia by measuring an assembled nacelle without parts (such as the LSS) that you will model separately. It is possible, but not easy, to measure the center of mass and inertias.

Another method is to compute the total nacelle properties by adding in the effects of each component. If appropriate, treat each component as a single-point mass. This is probably the easiest method if you have all the component masses and locations. You may want to compare the total computed mass to a weighed nacelle and modify the numbers to get them to agree.

You can specify the nacelle shroud geometry to permit animated graphics.

DRIVE TRAIN:

If you want to model your turbine with steady-state rotor motion, you can connect the hub to the nacelle with a revolute joint (hinge) and drive it with a MOTION statement. You will need only the rotor revolutions per minute (RPM), the shaft tilt, and the location of the attachment of the hub to the nacelle.

We approximate the generator by using Thevenin's Theorem (Fitzgerald, Kingsley, and Umans 1983, 424-427) to relate shaft slip to torque. This theorem really only applies for operation near steady state, but you can use it as a crude approximation for startups. For this, you will need to get some values off the nameplate and others from the manufacturer. From the nameplate, get the actual RPM, line-to-line voltage, and frequency. From the manufacturer, get the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance, magnetizing reactance, and iron-core-loss resistance.

For the gearbox, *ADAMS* does have a standard gear, but it is a perfect one; it does not model backlash. You will need to know the gear reduction to model this. Using user-written subroutines, you can create models of your generator and/or gear box in even greater detail.
You can model shafts as rigid parts; as simple, rotational spring/dampers assuming the shaft does not bend; or as distributed-mass, flexible beams. For a rigid shaft you need only mass, center of mass, mass moments of inertia, shaft tilt, and the point of attachment. For a spring/damper shaft, you will also need the spring and damping constants of the shaft. To model a fully flexible shaft, you will have to divide it into lumped masses in a fashion similar to the flexible tower.

HUB:

For a three-bladed rotor, you can adequately model the hub as a rigid body. For this, you need the mass, center of mass, and mass moments of inertia. You will also need the attachment points for the LSS and the blades. You will need the rotor precone angle to create the blade attachment joints. As always, geometry information is useful for animations.

For a two-bladed, teetering rotor, in addition to the data required for three-bladed rotors, you will need the undersling, the delta-3 angle, the contact angle for the teeter mechanism, and the stiffness and damping of the teeter stops. You may want to use a flexible model of the hub. For this, use the tower-modeling approach.

BLADES:

Blades are the most difficult part of the turbine to model. You will need to discretize the blades into lumped masses and specify their locations. You can connect the masses with rigid joints, flexible beams, or flexible fields. At NREL, we model our blades as both rigid and as flexible beams. Having the option to make the blades rigid is useful for checking out aerodynamics.

To make a rigid blade model, divide the blade into discrete masses and specify the centers of mass, mass moments of inertia, twist, chord, and thickness. You must also specify the pitch of the blade.

To create a flexible-beam blade model, augment the above information. Using the "lumped-mass" approach, divide the blade into beams that connect the discrete masses. As for the tower, *ADAMS* needs to know the beam lengths, their cross-sectional areas, area moments of inertia, Young's moduli, shear moduli, and the damping ratios or matrices. If the elastic axis does not pass through the centers of mass, you should specify this offset. To use fields, you must generate the stiffness matrix instead of area moments of inertia and moduli.

A modal survey of your blade (if available) will considerably improve the accuracy of the model. You can use *ADAMS/Linear* to generate eigenvalues to compare to the modal survey. By tweaking the moduli, area moments of inertia, and damping matrices, you can adjust your blade model's natural frequencies and damping to reflect the modal survey. If you decide to use fields you will have the stiffness and damping matrices to work with.

Some turbines have tip brakes. If yours does, you will need their masses and locations. You may also want to specify their geometry for graphics output.

AERODYNAMICS:

We use aerodynamics subroutines developed at the University of Utah to compute normal and tangential forces applied to points along the blade. They wrote a user's guide (Hansen and Davis 1994) that lists input data requirements for the aerodynamics routines. Additionally, if the centers of pressure are not aligned with the centers of mass you will need their offsets when placing the force vectors in *ADAMS*.

WINDS:

The University of Utah aerodynamics routines uses wind in three ways. First, you can specify constant hub-height, horizontal and vertical wind speeds, and horizontal and vertical wind shears. It is also possible to specify a file that contains time-varying winds, and you can change the code to read the kind of information that interests you. The third method is to specify files that contain time-varying u, v, and w component wind speeds for a grid that encompasses the rotor disk. This last method uses the output of NREL's *SNLWIND-3D* turbulence model.

REFERENCES:

Hansen, Craig; Davis, Dean. 1994. *User's Guide to AeroDyn the Wind Turbine Aerodynamics Model for ADAMS®*. Version 9.0. Salt Lake City: University of Utah.

Fitzgerald, A. E.; Kingsley, Charles Jr.; Umans, S. D. (1983). *Electric Machinery*. 4th ed. New York: McGraw-Hill Book Company.

TABLE OF PARAMETERS FOR MODELING WIND TURBINES WITH *ADAMS*

TOWER:

Rigid

Tower height (location of yaw bearing)
Tower geometry (for graphics)

Lumped-Mass Flexible Beams

Tower height (location of yaw bearing)
Mass of lumped masses
Locations of lumped masses
Mass moments of inertia of lumped masses
Beam lengths
Beam cross-sectional areas
Beam area moments of inertia
Young's moduli
Shear moduli
Damping "ratio" or damping matrix
Tower geometry (for graphics)

Lumped-Mass Flexible Fields

Tower height (location of yaw bearing)
Mass of lumped masses
Locations of lumped masses
Mass moments of inertia of lumped masses
Beam lengths
Stiffness matrix
Damping "ratio" or damping matrix
Tower geometry (for graphics)

Massless Spring-Damper Guys

Guy geometry (attachment points and length)
Spring constant
Damping constant
Guy pretension

Lumped-Mass Flexible Guys

Guy geometry (attachment points)
Mass of lumped masses
Locations of lumped masses
Mass moments of inertia of lumped masses
Spring constants for each segment
Damping constants for each segment
Guy pretensions for each segment

NACELLE:

If you choose to measure the total nacelle

Total nacelle mass
Mass moments and products of inertia
Nacelle center of mass
Location of yaw bearing
Location of beginning of separately modeled drive train
Nacelle shroud geometry (for graphics)

If you choose to derive properties from components

Component masses
Mass moments and products of inertia of large parts
Component centers of mass
Nacelle shroud geometry (for graphics)

DRIVE TRAIN:

Steady-state rotor motion

Rotor RPM
Shaft tilt
Hub attachment location

Steady-state generator

Actual RPM
Line-to-line voltage
Frequency
Stator resistance
Stator leakage reactance
Rotor resistance
Rotor leakage reactance
Magnetizing reactance
Iron core loss resistance

Perfect Gearbox

Gear ratio

Rigid Shafts

Shaft mass
Center of mass
Mass moments of inertia
Shaft tilt
Attachment points
Shaft diameter and length (for graphics)

Spring/damper shafts

Shaft mass
Center of mass
Mass moments of inertia
Shaft tilt
Attachment points
Spring constant
Damping Constant
Shaft diameter and length (for graphics)

Flexible shafts

Mass of lumped masses

Locations of lumped masses
Mass moments of inertia of lumped masses
Beam lengths
Beam cross-sectional areas
Beam area moments of inertia
Young's moduli
Shear moduli
Damping "ratio" or damping matrix
Shaft tilt
Attachment points
Shaft diameter and lengths (for graphics)

HUB:

Rigid hubs
Mass
Center of mass
Mass moments of inertia
Location of LSS attachment
Location of Blade attachments
Geometry information (for graphics)

Flexible hubs
Hub geometry for animations
Mass of lumped masses
Locations of lumped masses
Mass moments of inertia of lumped masses
Beam lengths
Beam cross-sectional areas
Beam area moments of inertia
Young's moduli
Shear moduli
Damping "ratio" or damping matrix
Geometry information (for graphics)

BLADES:

Rigid blades
Mass of lumped masses
Centers of mass
Mass moments of inertia
Blade structural twist
Blade aerodynamic twist
Blade chord and thickness (for graphics)
Tip brake mass
Tip brake center of mass
Tip brake moments of inertia

Flexible beam blades
Mass of lumped masses
Centers of mass
Mass moments of inertia
Blade structural twist
Blade aerodynamic twist
Beam lengths

Beam cross-sectional areas
Beam area moments of inertia
Young's modulus for each beam
Shear modulus for each beam
Damping ratios or matrices
Eigenvectors from modal survey if available
Blade chord and thickness (for graphics)
Tip brake mass
Tip brake center of mass
Tip brake moments of inertia

Flexible field blades

Mass of lumped masses
Centers of mass
Mass moments of inertia
Blade structural twist
Blade aerodynamic twist
Beam lengths
Stiffness matrix for each beam
Damping ratios or matrices
Eigenvectors from modal survey if available
Blade chord and thickness (for graphics)
Tip brake mass
Tip brake center of mass
Tip brake moments of inertia

AERODYNAMICS:

University of Utah Aerodynamics

See University of Utah user's guides
Centers of pressures

WINDS:

Steady wind

Horizontal wind speed
Vertical wind speed
Horizontal wind shear ratio (linear)
Vertical wind shear (ratio for linear, exponent for power-law)

Time varying wind

Horizontal wind speed time history
Vertical wind speed time history
Wind direction time history
Horizontal wind shear ratio (linear) time history
Vertical wind shear (ratio for linear, exponent for power-law) time history

Full-field turbulent wind

Time history of *u*, *v*, and *w* translational component winds (generated by SNLWIND-3D)